COMPARISON OF TOLLS WITH ESTIMATED FULL MARGINAL COSTS: THEORY MEETS REALITY

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Abstract
In this paper, we attempt to estimate the additional tolls that can be charged to drivers at the New Jersey Turnpike using the full marginal cost functions. The available data set used in this study consists of individual vehicle records in 2005 at the NJTPK. Vehicle-by-vehicle entry/exit times, entry/exit locations, vehicle types, payment type of each vehicle are available in the data set. From this dataset it is possible to calculate the hourly link volumes, car/truck distribution at each link and travel times between all origin-destination pairs. Using the NJTPK specific data and the developed cost functions, we estimate the range of the additional tolls for various OD pairs. We show that the estimated values highly depend on value-of-time assumptions and the choice of the travel time function. Furthermore, the differences between the estimated additional tolls during peak and off-peak are also presented.
INTRODUCTION

There has been much debate over recent plans about the future of the New Jersey Turnpike (NJTPK). Although there are not any official proposals on this issue yet, the likely option for NJTPK is to raise tolls and divert only the increased revenue to establish a new public corporation. This corporation would then issue bonds backed by that revenue. The amount of the bonds would be based on the value of the toll increases \((1)\). The Governor’s office has recently suggested that raising tolls at the rate of inflation every year over a period of decades could produce substantial revenues \((2)\).

Since its inception in 1951, NJTPK tolls have been increased only five times. These occurred on March 23, 1975, April 1, 1980, March 17, 1991; September 30, 2000; and January 1, 2003. The highest toll increase was in 1991: 70% for passenger cars and 100% for commercial vehicles \((3)\).

The toll rates are determined so that the annual revenue would cover administrative and operating costs of the facility. In general, the toll hikes have been enacted to pay for new widening projects. Smith \((4)\) stated that “…public works be so managed, as to afford a particular revenue for defraying their own expense, without bringing any burden upon the general revenue of the society.” He also mentioned that when vehicles pass over a highway they should pay toll in proportion to their weight. Namely, they pay for the maintenance of the public works in proportion to the wear and tear they cause to the infrastructure. This is to some extent how toll rates are being implemented in NJTPK. The current NJTPK toll charges are based on the distance traveled and vehicle classification. For example, a passenger car traveling the entire 122-mile length of NJTPK pays $6.45; and a six-axle truck pays $26.55. Cash toll rates at NJTPK, however, do not vary for time-of-the-day or for day-of-the-week. Only vehicles that pay toll electronically (E-Z pass) get lower rates. In particular, passenger cars with E-Z pass have lower rates during off-peak hours, and trucks with E-Z pass have a lower rate at any time of day.

On the contrary, in modern transportation economics theory, “tolls have been looked upon not as a means of financing road construction and maintenance, but as a means of bringing the best utilization of the highway network” \((5)\). Therefore, it has long been argued that drivers should face a price that is equal to the social marginal cost, instead of the average cost.

The full costs of highway transportation are usually categorized as direct and indirect costs. Direct costs (sometimes also called private or internal costs) include the costs that auto users directly consider in making a trip, such as vehicle operating cost, car depreciation, time lost in the traffic, tolls and other parking fees, etc. Indirect costs (also called social or external costs), on the other hand, refer to the costs that auto users are not held accountable for. These include the congestion costs that every user imposes on the rest of the traffic, costs of accidents (only those not borne through motor vehicle insurance fee), and costs of air pollution and noise.

Full Marginal Cost (FMC) means the overall costs accrued to society from servicing an additional unit of traffic. FMC includes capital costs, maintenance costs, accident costs, congestions costs and environmental costs.

The main objective behind the accurate estimation of FMC is to ensure that prices paid by highway users correctly reflect the true costs of providing the services. Optimal user charges should be set equal to the value of the resources consumed through the use of the transportation facilities.

In this paper, we attempt to estimate the additional toll charges that can be imposed on the users of the NJTPK using the full marginal cost functions most of which was estimated as part of another study \((6)\). It does not by any means advocate any sort of pricing policy or propose a different or better tolling rates at the NJTPK. It merely utilizes the commonly used economic theory with the available network specific data for estimating the additional tolls, and how these tolls vary with model assumptions. This analysis can be of interest to policy makers and analysts.
for better insight to the current issue in hand. The paper also points out these caveats in the estimation analysis.

MARGINAL COST PRICING AND REAL-WORLD ISSUES

Basic Formulation of Trip Based FMC

The cost of a trip between an OD pair in a network is defined as a function of several variables denoted by \( V_j \). The average cost \( C_{rs} \), of “one trip” performed between a specific OD pair \((r, s)\):

\[
C_{rs} = F(V_j; q)
\]  

(1)

where, \( q \) denotes the demand between the OD pair and \( F(V, q) \) is the cost function. It is assumed that there are \( q \) number of homogeneous users making the same trip at a given time period. The Full Total Cost (FTC) of providing a transportation service between any OD pair for \( Q \) trips is:

\[
FTC_{rs} = Q \cdot (C_{rs}) = Q \cdot F(V_j; Q)
\]  

(2)

The Full Marginal Cost (FMC) for each OD pair over a given time period is then:

\[
FMC_{rs} = \frac{\partial (Q \cdot F(V_j; Q))}{\partial Q} = F(V_j; Q) + Q \cdot \frac{\partial F(V_j; Q)}{\partial Q}
\]  

(3)

This function defines the cost of an additional trip in the system. The first term represents the average costs (also called “private average costs”), which is experienced by users. In Figure 1, the average cost includes travel time costs, vehicle-operating costs, and road usage costs. While travel time and vehicle operating costs are experienced directly by users, road usage costs are experienced through vehicle taxes or through tolls in the NJTPK case. Note that state or federal tax revenues are not used to fund the NJTPK.

The second term in equation (3) is externality or congestion costs, representing the additional costs to all users from an additional trip. It equals \( Q \cdot (\partial F(V_j; Q) / \partial Q) \). In Figure 1, the difference between the average cost and the marginal cost curves corresponds to this value and is equal to the optimal toll imposed on all users.

Thus, \( FMC \) of an additional trip is defined as:

\[
FMC \text{ (}) = \text{ Private Average Cost (}) + \text{ Congestion Related Costs (}}
\]
In the absence of such a toll, traffic flow will be $Q_0$ (at point $0$, where demand curve intersects with AC curve) with the corresponding average cost of a trip $C^0$. The social optimal is found at the point of intersection, $E$, where FMC and the inverse demand curve, $d(Q)$, intersect. To support the optimum, vehicles must face a cost of $C^E$. This can be accomplished by imposing a toll of $C^E - C^1$, which is equal to the marginal external cost of a trip, i.e. the cost imposed on the rest of the traffic by making an extra trip. This toll will evidently result in decrease in demand from $Q_0$ to $Q^E$. The reduction ($Q_0 - Q^E$) is the desired traffic flow effect of congestion pricing.

Discussion

The basic model shown in Figure 1 is attractive and helps understand the concept of congestion pricing. However, there are several important points that need to be addressed. In the NJTPK case, vehicles pay for two types of costs. The first is the private cost (e.g. travel time cost, vehicle operating costs such as gas, wear and tear on their vehicles, etc.). The latter is the toll for using the facility as imposed by the authority. The sum of all these costs equals to their average cost of traveling on the facility. It should be reasonable to assume that this cost is equal to $C^0$ in Figure 1. However, the social optimum at point $E$, where vehicles must be made to face a cost of $C^E$, cannot be determined simply by observing the equilibrium where AC meets the demand curve. For mathematical solution for finding point $E$ and the congestion toll, it is necessary to estimate AC and demand curves (10). Although we can estimate AC curve, unfortunately, the estimation of such a demand function is usually not straightforward for complex traffic networks.

Nevertheless, if AC curve and therefore FMC cost curve can be estimated, $C^A - C^0$ can be calculated at the demand level $Q^0$. This value is the difference between the value of FMC and AC at $Q^0$ in Figure 1. It can be argued that $C^A - C^0 \geq C^E - C^1$, if FMC is greater than or equal to AC. We regard $C^A - C^0$ as the upper bound of the toll for NJTPK users. Henceforth, this upper bound value will be called the “estimated additional toll.”

It should be noted that estimated additional toll due to congestion does not necessarily eliminate congestion, since cost of travel at demand $Q^E$ is still higher than the cost under free-flow conditions, $C^E$. Therefore tolling can be marketed only as a means for alleviating congestion, not eliminating it (10).
Hypercongestion (unstable flow), as shown by the backward-bending section of the AC curves in Figure 1, has a non-unique relationship between flow and travel time (cost). This section of the curve suggests that if quantity (traffic flow) were reduced by a certain amount, it would yield increase in travel time. Hypercongestion cannot be captured by static traffic models. Various dynamic models have been proposed in the literature, e.g. Small and Chu (11) and Verhoef (12). It is shown in the following sections of the paper that, although it seems very rare, such hypercongested traffic regimes are observed in certain locations of the NJTPK. Hypercongestion traffic regimes are omitted in our analyses.

The next section is devoted to the estimation of functions for each cost category as well as the data used in the analysis.

**COST FUNCTIONS**

Operating costs of the NJTPK include but are not limited to executive office, administrative and technology services, maintenance, engineering, employee benefits, procurement, communications and law. Most of these cost components are fixed costs, meaning they are not directly related to the traffic flow in the facility.

The cost of maintenance works, however, is clearly related to traffic flow. By maintenance costs, we imply roadway resurfacing, bridge deck repair, striping, and such type of maintenance work. There are also the cost of new construction and widening projects. However, estimating their relationship with traffic volume is not straightforward.

All of these cost components, whether a function of traffic volume or not, are recovered through tolls in the NJTPK. Therefore, we associate these costs to the vehicle operating cost in the NJTPK. In other words, these costs are out-of-pocket costs for the users of the NJTPK.

**Congestion**

Congestion costs can be defined as the drivers’ time loss and discomfort in the traffic. Its value depends on travel time and the value of time of vehicles.

The Bureau of Public Roads (BPR) travel time function is a well-known and commonly applied travel time function due to its simplicity. It is in the following mathematical form:

\[
t = t_f (1 + \alpha \left( \frac{Q}{C} \right)^\beta)
\]

where \(t\) and \(t_f\) are congested travel time and free flow link travel times, respectively. \(Q\) and \(C\) are traffic volume and capacity per hour; \(\alpha\) and \(\beta\) are model parameters. Commonly utilized values for the model parameters are \(\alpha = 0.15\) and \(\beta = 4.0\).

Total congestion cost for all vehicles per hour can be estimated using equation (4) as follows:

\[
C_c = Q \cdot t \cdot VOT
\]

\(VOT\) stands for the value-of-time of vehicles. Depending on the mode used by the traveler, travel time costs may include time devoted to waiting, accessing vehicles, and actual travel. Its value varies between $6.4 – $40.6 per hour (14). In our analysis, we use $7.6 per hour as the VOT as used in Ozbay et al. (6). Variation of results with different VOT assumptions is also presented.

The marginal congestion cost can be formulated as follows:
\[
MC_c = \frac{dC_c}{dQ} = t \cdot VOT + Q \frac{dt}{dQ} VOT
\] (6)

The first part of the first term in the right-hand side is the congestion cost that the additional drivers experiences, and the latter one is the congestion cost that he imposes on the rest of the traffic.

If \( \alpha \) is fixed, for any value \( \beta \) we have \( t = 1.15 t_j \) when volume is equal to capacity. In such cases, speed varies only by 13%, and the differences in speed values are minimal when \( Q / C < 1 \) for any value \( \beta \). However, when \( Q / C > 1 \), speed reaches zero faster for higher \( \beta \) values. For example, when \( \beta = 4.0 \), speed reaches to zero when \( Q / C > 4 \).

Higher \( \alpha \) values reduce speed faster, particularly when volume is less than capacity. Figure 2 shows the variation in speed for different values of \( \alpha \) when \( \beta = 4.0 \).

It is evident that the selection of model parameters has a big impact on how speed changes with \( Q / C \). For planning models, the BPR function is desirable because volume is higher than capacity during the initial iterations of network loading. Even then, the convergence of network loading slows down for high values of \( \beta \) (15).

**Figure 2.** BPR speed functions for various \( \alpha \) values and \( \beta = 4.0 \)

Another limitation of BPR function is that it cannot capture the hypercongested traffic flow conditions. As mentioned earlier, hypercongestion is a real phenomenon and occurs when volume exceeds capacity somewhere in the system. This results in queue formation and becomes more severe as more vehicles are added to the queue. As demand falls back below the level that causes the queue formation, queue length starts reducing and the system goes back to ordinary congestion (11).

**Figure 3** demonstrates the speed-flow relationship at two selected segments on the NJTPK, namely between interchanges 14 and 14A and 18W and 16W. The distance is 3.5 miles and 1.1 miles, for 14-14A and 18W-16W, respectively.

The speed and volume per hour information were extracted from the available NJTPK dataset. The description of the NJTPK network and the available dataset is presented in the next section. However, it suffices to mention that the speed values in this figure are space mean speeds of E-Z pass vehicles (E-Z pass vehicles have transponders on their windshield where they automatically pay at toll plazas by reducing their speeds to 5-10 mph). For example, between
interchange 14 and 14A, travel time of a vehicle is measured from the time it enters the network through the interchange 14 entry toll plaza and the time when it exits at interchange 14A exit toll plaza. Clearly, the space mean speed is lower due to the fact that vehicles slow down at entry and exit toll plazas.

Figure 3a shows the speed-flow relationship at 14-14A. The figure shows that although most speed data falls on the ordinary congested region, it is evident that traffic was in the hypercongested region in some instances. Furthermore, the speed falls below 30 mph when volume exceeds 1,500 vehicles per hour per lane (vphpl). According to the NJTPK traffic engineers the capacity at NJTPK varies between 1,850 – 2,100 vphpl. Then, Figure 3a tells us that speeds reduce by approximately 50% when $Q/C$ is between 0.7 and 0.8. On the other hand, at 18W-16W, the speed does not change as much with increasing $Q/C$. When $Q/C$ is between 0.7 and 0.8, speeds reduce by at most 10%. Nevertheless, the distribution of speed values in Figure 3b also shows evidence of hypercongestion at 18W-16W.

![Speed-flow curve at selected segments on the NJPTK](image)

**Figure 3.** Speed-flow curve at selected segments on the NJPTK

As discussed in the previous section, although we can observe instances of hypercongestion in the NJTPK, these are few in number as compared to ordinary congested traffic flows. Derivation of dynamic traffic flow model is out of the scope of this paper. Therefore, we use the BPR travel
time function in the analysis, yet we present the sensitivity of the results with different values of the model parameters.

Accidents

One would assume that accident occurrence on a roadway is more probable when the number of vehicles is higher. Also, the probability of occurrence would change with roadway design characteristics, such as such as number of lanes, horizontal and vertical alignment, and sight clearance and obstructions. There is abundant number of studies in the literature that deal with functions that relates these variables with the number of accidents per time period. Readers might refer to Ardekani et al. (17) for an extensive review of these functions.

Analysis of historical accident data for the NJTPK shows that there is clear relationship between the annual number of accidents and the number of vehicles. The dataset include the annual number of accidents by type and the annual number of vehicles traveled for each year from 1952 to 2006. Readers may refer to the online annual figures for the NJTPK at reference (16).

Regression analysis of this dataset suggests the following relationship between accidents and volume as follows:

\[ y = ae^{bQ} \]  (7)

Where, \( y \) is the annual number of accidents and \( Q \) is the annual number of vehicles in the NJTPK. The regression results are in Table 1a.

These results suggest that accidents increase exponentially with the number of vehicles. However, the coefficients given in Table 1a are valid for the network-wide number of accident per year and they are not valid for link traffic volumes that are in the range of 15,000-120,000 vehicles per day. Therefore, a second set of data is used for link-based estimation of an accident occurrence function. Dataset includes average annual daily traffic (AADT) and the annual number of accidents at each link in the NJTPK for 1996, 1998 and 1999. Table 1b shows the results of regression analysis. The function gives the number of accidents per mile with respect to AADT.

Table 1. Results of NJTPK accident regression analysis

(a) Network wide analysis

<table>
<thead>
<tr>
<th>Function ( y = ae^{bQ} )</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b )</td>
<td>1.015E-8</td>
</tr>
<tr>
<td>( a )</td>
<td>7.145</td>
</tr>
<tr>
<td>( R^2 = 0.952 )</td>
<td></td>
</tr>
<tr>
<td>Observations = 55</td>
<td></td>
</tr>
<tr>
<td>( Q ) is annual number of vehicles in NJTPK</td>
<td></td>
</tr>
<tr>
<td>( y ) is the annual number of accidents in NJTPK</td>
<td></td>
</tr>
</tbody>
</table>

(b) Link based analysis

<table>
<thead>
<tr>
<th>Function ( y = ae^{bQ} )</th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b )</td>
<td>2.00E-5</td>
</tr>
<tr>
<td>( a )</td>
<td>2.8092</td>
</tr>
<tr>
<td>( R^2 = 0.850 )</td>
<td></td>
</tr>
<tr>
<td>Observations = 94</td>
<td></td>
</tr>
<tr>
<td>( y ) is the number of accidents per mile</td>
<td></td>
</tr>
</tbody>
</table>
Based on the results shown in Table 1b, an accident cost function can be constructed by multiplying the accident occurrence function with a corresponding unit cost factor. FHWA (18) reported the unit costs of fatality, evident injury and property damage accidents as $3,932,730, $54,453 and $3,025, respectively. These numbers are converted to 2007 dollars using an annual 3% inflation rate. Since, we do not have specific accident cost functions for different accident types, an average accident unit cost is utilized. In NJTPK accident database (16), for 2004, 2005 and 2006, the average percentage of fatality, injury and property damage accidents are found as 0.3%, 16.1% and 84.6%, respectively. Multiplying the unit costs by the percentages for each accident type yields an average accident unit cost of $23,124 per accident.

Accident cost function and then the marginal cost function can then be formulated as:

\[ C_{acc} = 64,960e^{2E-5Q} \]  \hspace{1cm} (8)

\[ MC_{acc} = 1.3e^{2E-5Q} \]  \hspace{1cm} (9)

\( C_{acc} \) and \( MC_{acc} \) are defined as dollar per year. Note that based on these functions marginal accident cost is greater than average accident cost when link AADT is greater than 50,000 veh/day.

**Vehicle Operating**

Vehicle costs include the costs attributed to the vehicle owner. These costs are internal to the car owner and can be divided into two subcategories: fixed (insurance, registration, taxes), and variable (maintenance, repair, fuel, car value depreciation).

Here, we assume that only fuel consumption is in relationship with traffic volume. Fuel consumption function is adopted from Vincent et al. (19), and it is in the following form:

\[ F = 0.0723 - 0.00312V + 5.403E - 5V^2 \]  \hspace{1cm} (10)

\( V \) is average vehicle speed in mph and \( F \) is fuel consumption rate in gallons per mile. \( V \) depends on traffic volume \( Q \) by equation (4). An average fuel price of $3.00 per gallon is used as reported for New Jersey in 2006 (20). It should be mentioned that this average price is still valid for 2007 as well. Then vehicle-operating cost can be presented as:

\[ C_o = Q(3F + b) \]  \hspace{1cm} (11)

\( C_o \) is total vehicle operating cost, and \( b \) stands for the components of vehicle operating cost besides fuel cost. Then, the marginal vehicle operating cost can be given as:

\[ MC_o = 3F + b + 3Q \frac{dF}{dQ} \]  \hspace{1cm} (12)

In equation (12) externality of vehicle operating cost appears only in fuel consumption cost. (Only fuel cost is taken as a function of traffic volume. Therefore, the additional trip only affects the fuel consumption cost, not the other components of the vehicle operating cost).

In Ozbay et al. (17), \( b \) is estimated as

\[ b = 0.441t + 0.059d + Toll \]  \hspace{1cm} (13)

\( t \) is travel time in hours and \( d \) is distance in miles. The coefficient of \( t \) gives the depreciation of car value and insurance cost per hour (assuming an average age of all vehicles in the NJTPK as 6
years with 12,000 annual miles) and the coefficients of \( d \) gives the wear and tear, maintenance and oil cost per mile.

The additional cost in equation (13) is the toll charges, which connotes to the cost of providing infrastructure and operations, which are paid by users of the NJTPK. As mentioned earlier in the section, we consider toll charges as vehicle operating costs.

**Environmental**

Environmental costs due to highway transportation are categorized as air pollution and noise pollution costs. We have decided not to include these costs from the marginal cost estimations due to the following reasons:

Noise costs are omitted in our analysis since there are noise barriers around residential areas along the NJTPK. The contribution of noise costs on FMC can therefore be assumed minimal. Furthermore, since the construction cost of noise barriers are paid through toll revenues, we can assume that the drivers already pay for the noise costs.

The effect of air pollution is far-reaching yet not sudden; and the precise estimation of its costs is not a straightforward task. Cost values acquainted with air pollution require a detailed investigation and an evaluation of people’s preferences and their willingness to pay in order to cover the adverse effects. Any unit value per pollutant can be negotiable to another researcher. As Small (21) stated: "The primary argument against quantifying environmental effects in monetary terms is that doing so adds considerable uncertainty to the resulting evaluation, while lending an unwarranted aura of precision and completeness." Therefore, we omit this cost function from our analysis as well.

Detailed analysis on both cost functions can be found in Ozbay et al. (8).

Finally, FMC and AC functions used for the analysis presented in the next section can be presented as follows:

\[
FMC = MC_c + MC_{acc} + MC_o + MC_m
\]

\[
AC = AC_c + AC_{acc} + AC_o + AC_m
\]

**DATA ANALYSIS**

**Network Description**

NJTPK is a 148-mile toll facility. Toll collection is performed using a closed-ticked system. Each interchange in the facility has entry and exit toll plazas. Vehicles enter the facility at an interchange’s entry toll plaza, and when they leave the facility at another interchange they pay the toll, which is based on their entry interchange. There exist 29 operational interchanges in NJTPK with average daily traffic exceeding 500,000 vehicles. It is one of the principal north-south highway corridors in New Jersey. It is a direct connection between Delaware Memorial Bridge in the south and the George Washington Bridge, Lincoln Tunnel and Holland Tunnel to the New York City in the north. Figure 4 shows the NJTPK map and the milepost of each interchange.
Figure 4. New Jersey Turnpike Map (not to scale) and interchange milepost table

Data Description

NJTPK data set used in this study consists of individual vehicle records in 2005. Vehicle-by-vehicle entry/exit times, entry/exit locations, vehicle types, payment type of each vehicle is available in the data set. From this dataset it is possible to calculate the hourly link volumes, car/truck distribution at each link and travel times between all origin-destination (OD).

In order to conduct cost estimation, a computer program is coded in C programming language for parsing this dataset (one month of data is approximately 1GB in text file format).
Results

The available dataset is extensive and it provides precise hourly link volume data and vehicle distributions at each link for the entire period in 2005. The quality of data is very important for the validity of estimation results. However, as mentioned in the earlier section, there are many assumptions that one needs to consider during the development of cost functions. Therefore, the results are highly dependent on these assumptions and therefore should be presented accordingly.

Using the cost functions presented in the previous section, we have estimated the average and marginal costs between each interchange for each hour in 2005.

The number of OD pairs in the network is very high and this makes it difficult to present the marginal and average cost of each pair. Therefore, we first present the estimation results for trips between selected OD pairs during the morning peak period between 7 a.m.-8 a.m. on weekdays.

Table 2 shows the average and marginal cost by each category with corresponding toll charges for passenger cars and 6-axle trucks.

Discussion about current toll rates: The toll charts for all vehicle categories are available in the NJTPK website. Due to the space limitations we are not able to insert this table here. If we calculate the toll rates given in Table 2 per distance, we can deduce that traveling between some OD pairs are substantially more expensive per mile than other OD pairs. Toll rates for passenger cars vary from $0.04 to $1.85, and for 6-axle trucks from $0.05/mile to $0.64/mile. These rates become more for the OD pairs in the northern sections of the NJTPK. This can be attributed to high traffic volumes at these sections due their proximity to the New York City and other major highways, bridges and tunnels.

An interesting observation about the current tolling rates is that short trips are charged more than longer trips. It can be seen that a continuous trip from interchange 1 to interchange 14 is less expensive than the total cost of tolls between connecting OD pairs along the path. In other words, if we add up the toll costs along this path, such as 1-2, 2-3,..., 13A-14, the cost of this trip becomes $8.70 and $30.45, whereas the cost of traveling between 1-14 is $4.95 and $22.00 for passenger cars and 6-axle trucks, respectively.

It can be seen in Table 2 that the major contribution to FMC is from private (or average) congestion costs. However, when external costs are considered (FMC-AC), the contribution of congestion externality and accident externality are almost equivalent.

The last column shows the estimated additional toll due to congestion and accidents (We see no significant externalities in vehicle operating costs. The difference between marginal and average vehicle operating costs is therefore minimal). It should be noted that this value represents the estimated additional toll for passenger cars. A corresponding value for other vehicles can be calculated by the same factor used in the toll charts (i.e. the ratio of column 3 and 4). Also, as mentioned earlier, these values are by no means optimal tolls, but upper bounds for optimal tolls. Thus, optimal values should be expected between the current tolls and the values given in the last column of Table 2.

The results show that OD pairs 1-2, 2-3, 6-7 and 16W-18W yield almost the same FMC and AC values. For the other OD pairs given in the table, when FMC is greater than AC, the comparison of the estimated additional toll with respect to the current tolls suggest that during 7 a.m.-8 a.m. the highest toll should be less than 64 cents (or 55 cents if only congestion externality is considered).

However, Table 2 includes only adjacent OD pairs. There are approximately 650 OD pairs with different distances in the network. When we normalize the estimated additional tolls by trip distance, within all OD pairs during the morning and afternoon peak hours, the highest estimated additional toll is found as $0.111 per mile between interchange 13 and 13A during 7 a.m.- 8 a.m. It can be observed from Table 2 that the external accident cost between this OD pair is high. If
only congestion externality is considered, then the highest estimated additional toll is found as $0.089 per mile between interchange 8 and 8A during 7 a.m. – 8 a.m.

**Table 2.** Cost estimation by category between selected OD pairs during 7 a.m.- 8 a.m.

<table>
<thead>
<tr>
<th>O</th>
<th>D</th>
<th>Current Toll</th>
<th>Passenger Car</th>
<th>Current Toll</th>
<th>6-axle Truck</th>
<th>$MC_c$</th>
<th>$AC_c$</th>
<th>$MC_{acc}$</th>
<th>$AC_{acc}$</th>
<th>$AC_o$</th>
<th>FMC</th>
<th>AC</th>
<th>Estimated additional Toll</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>0.65</td>
<td>2.15</td>
<td>0.0316</td>
<td>1.23</td>
<td>0.19</td>
<td>0.26</td>
<td>1.26</td>
<td>2.71</td>
<td>2.75</td>
<td>-0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.65</td>
<td>2.15</td>
<td>0.0856</td>
<td>1.53</td>
<td>0.24</td>
<td>0.31</td>
<td>1.13</td>
<td>2.99</td>
<td>2.98</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
<tr>
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Notes: (1) Private congestion and average congestion costs ($AC_c$) are equal to each other. (2) There are insignificant differences between marginal and average vehicle operating costs ($AC_o$), since the externality due to increased volume is very small. (3) AC and FMC values shown above do not include the current tolls. Due to equation (12), in the FMC-AC term the current toll cancels out.

It should be pointed out that the average and marginal cost values, and therefore the estimated additional toll change with various assumptions in the development of cost functions. For example, congestion externality is a linear function of VOT values. If we assume that VOT is equal to $18.0 per hour, then the estimated additional toll between 8-8A during 7 a.m.- 8 a.m. becomes $0.021 per mile.

Likewise, the coefficient values, $\alpha$ and $\beta$ in the BPR travel time function can substantially change the estimated additional tolls. For example, when the cost estimation analysis is repeated for 2005 with $\alpha=0.60$ and $\beta=4.0$, the estimated additional toll between 8-8A during 7 a.m. – 8 a.m. is $0.355 per mile for VOT = $7.6 per hour, and $0.842 per mile for VOT = $18 per hour.

Figure 5 demonstrates the distribution of the estimated additional toll per mile of all OD pairs during the peak hours for $\alpha=0.15$ and $\alpha=0.60$ when $\beta=4.0$. It can be observed that the majority of the estimated additional tolls is less than 8 cents per mile when $\alpha=0.15$, whereas the additional tolls vary from 4 cents to 20 cents per mile when $\alpha=0.60$. This figure gives a clear idea of how much the travel time function can affect the cost estimates.
Figure 5. Estimated additional toll per mile distributions during peak hours

It has been suggested in the literature that tolls should not be a fixed value for different times of the day and different days in the week. Vickrey (23) stated that: “…in nearly all other operations characterized by peak-load problems, at least some attempt is made to differentiate between the rates charged for peak and for off-peak service. Where competition exists, this pattern is enforced by competition: resort hotels have off-season rates; theaters charge more on weekends and less for matinees. Telephone calls are cheaper at night…”

We have generated the cost estimation results for the same OD pairs presented in Table 2, but this time for off-peak hour travel, in particular between 8 p.m.- 9 p.m. The results are shown in Table 3.

Table 3. Cost estimation by category between selected OD pairs during 8 p.m.- 9 p.m.

<table>
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<th>O</th>
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<th>Current Toll</th>
<th>Current Toll</th>
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<th>$AC_c$</th>
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*See the notes in Table 2.
It can be observed that the estimated additional tolls are lower than those shown in Table 2. Although the difference is not highly significant, negative additional toll can be considered as drivers paying higher tolls than estimated.

This result is expected, because it is evident that during off-peak hours the network is not fully utilized. Therefore, if additional tolls were to be charged, one would expect incentives to drivers for using off-peak or peak-shoulder period. The estimated additional tolls given in Table 3 are considerably lower than the estimated additional peak-hour tolls. For instance, the estimated additional toll for OD pair 8-8A is $0.12 for off-peak period, whereas this value is $0.64 for morning peak period. The estimated additional toll for 8-8A during off-peak period becomes $0.17 for $\alpha = 0.60$ and $\beta = 4.0$ in the BPR travel time function.

It should be noted that the average and marginal accident cost estimates shown in Table 2 and Table 3 are the same. This is because AADT is utilized as a variable in the accident occurrence function. Therefore, the function estimates the same number of accidents at any given time of the day. One would expect that accident occurrence is higher during peak hours than off-peak hours. Further improvement of the accident cost function is left as a future work. Even so, if only congestion externality is used to determine tolls, the difference between peak and off-peak values become even more substantial. $MC_e$ values given in Table 2 are practically zero between the selected OD pairs. The difference between congestion externalities of all OD pairs during 7 a.m.–8 a.m. with 8 p.m.-9 p.m. is plotted in Figure 6. It can be seen that during the off-peak period the majority of the estimated congestion externality is less than 20 cents, whereas during the peak-period this value reaches up to $1.2.

**Figure 6.** Comparison of congestion externalities for peak and off peak hours

**CONCLUDING REMARKS**

There are myriad of decisions when it comes to adjusting how much the tolls should be raised at a toll facility. It is indeed the case for the NJTPK. It has been publicized that the vital purpose of the proposed toll hikes is to generate additional income to close the budget deficit of New Jersey (1). Therefore, if the government decides to enact higher tolls, the new toll rates will then be adjusted based on this objective.
We have attempted to demonstrate how to estimate the tolls by utilizing commonly used economic theory. The results presented are not intended to give explicit answers to how much the tolls should be, but to show how much the answer can vary with the underlying assumptions in the development of cost functions. There are clear limitations to estimating the optimal tolls. These are listed in the Marginal Cost Pricing and Real World Issues section. The foremost limitation is the absence of a known demand curve for the NJTPK. We have shown that using the average and marginal cost curves, we can determine an upper-bound value for the optimal toll.

The data utilized in our analysis is nearly impeccable, providing us with hourly link volumes, vehicle distributions, trip distances and travel times. Even then, there is uncertainty when giving definite answers to the problem in hand. The uncertainty originates from the assumptions used in estimating the cost functions. The most crucial assumptions are the value-of-time (VOT) of drivers and the travel time function used in estimating congestion. With different VOT assumptions, the results can vary substantially. Fortunately, the results can be adjusted easily for any range of VOT, because it can be shown that congestion externality is a linear function of value-of-time. Similarly, the choice of travel time function highly affects the value of tolls. We have utilized a commonly used BPR travel time function. The results show that the estimation results changes significantly with the selected value of coefficients in the BPR function.

There are many origin-destination pairs in the NJTPK network. It is thus hard to present the results for each pair. Therefore, we have normalized the estimated additional tolls for each OD pair using the trip distances. Figure 5 demonstrates the change in toll per mile with the model parameter, $\alpha$, of the BPR function. We have found that when VOT is equal to $7.6$ per hour, the estimated additional tolls vary up to 142\% of the current toll charges for selected OD pairs during morning peak hour. The highest estimated additional toll converts to $0.089$/mile. Clearly, these numbers increase with increasing VOT and $\alpha$ values.

We have also showed that for off-peak hours the estimated additional toll is substantially lower than those estimated additional for the peak-hours. The distributions of estimated additional tolls are compared in Figure 6.

Finally, it is important to point out that the cost functions do not include air pollution costs. We have omitted these costs since the precise estimation of this cost category is not a straightforward task. Therefore, we should expect that the estimated additional tolls should be higher than the ones presented here.
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